AD-A141 487 SSN COMBAT SYSTEMS ENGINEERING AND ANALYSIS PROGRAM METHODOLOGY DEVELOPMENT(U) SUMMIT RESEARCH CORP GAITHERSBURG MD M BLACKSBERG 31 MAR 82 SRC-TR-70-82 1/1

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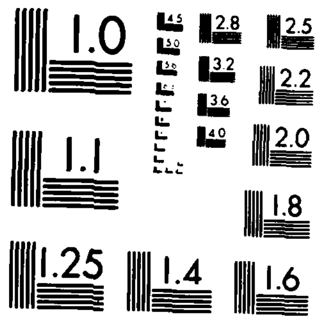

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SUMMIT RESEARCH CORPORATION

1 West Deer Park Road
Gaithersburg, Maryland 20760

SSN Combat Systems Engineering and Analysis Program Methodology Development

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CORPORATION

One West Deer Park Road
Gaithersburg, Maryland 20877

(301) 840-1707

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SSN COMBAT SYSTEMS ENGINEERING AND ANALYSIS PROGRAM METHODOLOGY DEVELOPMENT

SRC TECHNICAL REPORT NO. 70-82

31 MARCH 1982

BY

M. BLACKSBERG

PREPARED FOR:
DAVID TAYLOR NAVAL SHIP RESEARCH & DEVELOPMENT CENTER
BETHESDA, MD 20084

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CSE&A METHODOLOGY DEVELOPMENTS

INTRODUCTION

The Military Effectiveness Office (DTNSRDC 1806) has been supporting the NAVSEA (PMS 393) SSN Combat Systems Engineering and Analysis (CSE&A) Program by producing the Attack Submarine Development Plan (ASDP). As part of this effort, a methodology for evaluating the military payoffs of adding various advanced equipments to the baseline SSN 716 has been developed. This effort is directed at improving and extending the SSN CSE&A evaluation models dealing with three areas of SSN performance including:

1) SSN effectiveness in a moving barrier mission

2) SSN effectiveness in an area clearance mission

3) SSN effectiveness in multiple engagement scenarios.

This report documents the results of the effort up to the time when the task was terminated due to funding cutbacks. The barrier model was complete in its development except for the testing of the model which was

ongoing. The area clearance algorithm was developed but the model necessary for generation of results was not completed. No work was performed on multiple engagement effectiveness.

BARRIER MODEL

The barrier model was used to compute the probability that a submarine transiting a channel of width L_B at speed V_T will be detected at some time during its passage by a barrier submarine which patrols back and forth across all or part of the channel (L_P) at speed V_B. The transitor is assumed to be travelling perpendicular to the barrier since this is his best tactic to minimize detection opportunity.

For initial positions of transitor and barrier submarine shown in Figure 1A, the relative track of the transitor in barrier space (i.e., the barrier submarine is the fixed center of this moving coordinate space) is shown in Figure 1B. The initial direction of the barrier submarine is indicated by the arrow above the B which denotes the barrier submarine.

This relative path is only one of an infinite number of possible paths related to the initial positions of the transitor and barrier submarine. The transitor submarines initial position is uniformly distributed at some maximum range across the total barrier length. The barrier submarines initial position is uniformly distributed over the barrier patrol length with initial direction of travel either to the right or left. This is true except at the end points of the patrol at which only one direction is possible.

The barrier effectiveness then is the mean probability of detection over these infinite combinations of paths.

The probability of detection along a particular path is computed using a "relaxation time" model in order to deal with the correlation between samples taken continuously along the path. As stated in Reference 1, let

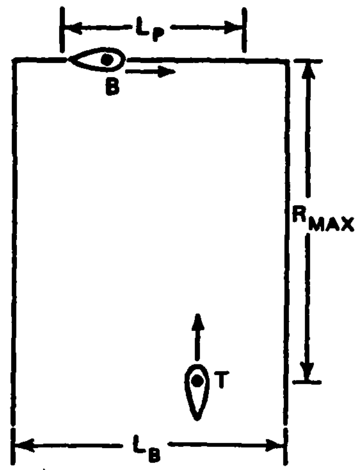

Figure 1A INITIAL TRANSITOR AND BARRIER SUBMARINE POSITIONS AND BARRIER DIMENSIONS

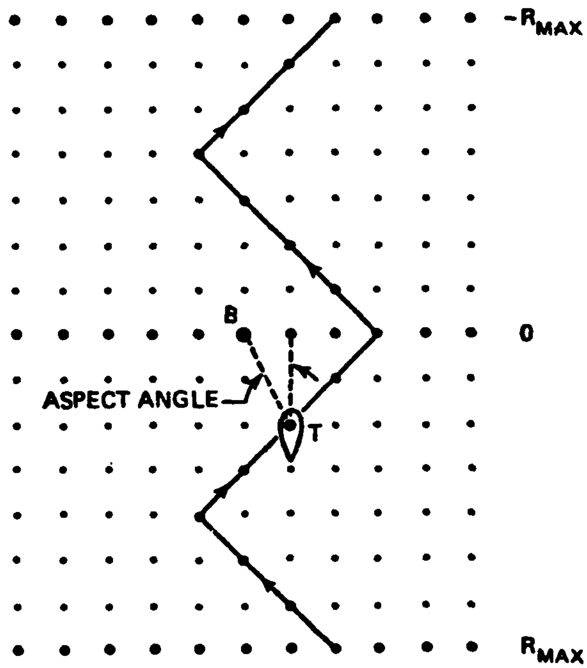

Figure 1B RELATIVE TRACK OF TRANSITOR IN BARRIER SUBMARINE SPACE

$x(t)$ be a 0-mean stochastic process and define $E(t) = e(t) - x(t)$ to be the time dependent signal excess where $e(t)$ is the "signal excess" computed from the relative position of target and receiver and by the FOM of the sensor. The probability of detection is then a first passage probability for $E(t)$ through the level 0. The simplest case is where $x(t)$ is constant over intervals, being chosen independently from a normal distribution with mean 0 and variance σ^2 in each interval. If the intervals all have the same length, the model is called the "relaxation time" model. In this case the probability that no detection occurs in the i^{th} interval is

$$q_i = 1 - \Phi(e(t_i)/\sigma)$$

where by definition the maximum of $e(t)$ in the i^{th} interval occurs at t_i and Φ is the cumulative normal function. The probability of detection along any path is then

$$p = 1 - \Pi_i q_i$$

where the product extends over whatever intervals are involved in the time period necessary to complete one relative track.

Having to break up the track into equal segments for the "relaxation time" model, also allows a reduction in the number of paths needed to be considered and an increase in computational efficiency when the length of the segments is chosen carefully.

The barrier length is divided into N equal segments that roughly correspond in length to the distance travelled by the barrier submarine in one relaxation time period. The relaxation time period is related to the macro-environmental fluctuations of the medium. The barrier submarine requires a time t_B to travel a distance equal to the length of one of these segments. The transitor meanwhile travels a distance $V_T t_B$ in the time t_B.

The transitor starts his run at a distance (R_{MAX}) from the barrier outside the maximum possible range of detection (that range for which the detection probability is at or near zero). The transitor travels M range segments of length ($V_T t_B$) to reach the barrier line from this initial range. After the transitor has moved from R_{MAX} to the barrier line, the barrier submarine has patroled M barrier segments back and forth from its initial position. At the barrier line the barrier submarine and the transitor will be separated by some number of barrier segments, as shown in Figure 1B.

In barrier space we have developed a grid of points, 2N+1 by 2M (R_{MAX} to - R_{MAX}) where the relative transitor track can be reconstructed by appropriately moving diagonally from one grid point to the next and where changes in the direction of diagonal movement correspond to the reversal of barrier submarines direction at the end of the patrol length. (See Figure 1B.)

If N_P segments out of the total N barrier segments are partolled (N - N_P must be a multiple of 2 to ensure that the patrol length is centered in the barrier) then there are N_P + 1 endpoints of the patrol segments. The barrier submarines initial position is allowed to be at any of these points, initially travelling in either direction, except at the end points of the patrol length where only one direction is possible. There are therefore $2N_P$ initial starting points (taking into account position and direction) that are possible for the barrier submarine. The transitor submarine may start at any one of the N + 1 points of the barrier length from a distance of M range segments from the barrier line. The total number of paths to be considered is $2N_P(N+1)$, accounting for all possible combinations of initial positions for transitor and barrier submarines.

The barrier model permits utilization of aspect dependent source level data. In barrier space, the transitor progresses along the relative track with heading perpendicular to the barrier line (Figure 1B). Thus for

any point in the grid, the aspect angle is the aspect presented to the center of the grid (barrier submarine). The probability of detecting the transitor when moving diagonally from one grid point to the next is the highest probability of detection (i.e., highest signal excess) in this segment. In computing detection probabilities with aspect dependent source level data, all terms of the signal excess equation remain constant except for the source level and propagation loss terms. The highest signal excess in a segment of relative track is found by determining the maximum of source level minus propagation loss for all points in that segment. If source level is assumed independent of aspect, the maximum signal excess for a segment of relative track occurs when the propagation loss is at its minimum in this segment since propagation loss is the only variable in the signal excess equation.

The probability of not detecting the transitor is computed for every grid point for the diagonal segments entering that grid point from the right and/or left, depending upon the physical possibility. Once the probability of not detecting is calculated for all grid points, an indexing scheme is used to calculate all possible tracks. This scheme is presented in Appendix A.

When reconstructing the $2N_p(N+1)$ possible tracks, most of these diagonal segments are included in more than one track. The computational efficiency of the model is therefore improved since the probability of not detecting in any segment is only calculated once even though it may be used in numerous track reconstructions.

The overall probability of detecting the transitor along any relative track is therefore $1-\Pi_i P$ (not detecting in segment i) and the barrier effectiveness is the average probability of detecting the transitor for all $2N_p(N+1)$ tracks.

BARRIER MODEL INPUTS

Inputs to the model are as follows:

Barrier Length (nm)
Number of Barrier Segments
Number of Patrol Segments
Velocity of transitor (knots)
Velocity of barrier submarine (knots)
Background Noise received by barrier submarine sensor (dB)
Recognition Differential of barrier submarine processor ( )
Source Level File (if aspect dependent data is used)
Propagation Loss File
Choice of:

a) Transitor submarine travels from R_{MAX} to the barrier line (o) or

b) Transitor submarine travels from R_{MAX} to $-R_{MAX}$

NOTE: R_{MAX} is the maximum possible range at which barrier submarine can detect transitor (probability of detection $\simeq .001$).

BARRIER MODEL BENEFITS

The barrier model as developed has numerous advantages over the use of the standard barrier probability of detection equations in which the barrier submarine patrols the barrier length to within a fixed distance (W/2)of the barrier end points (W/2 is one half the sweepwidth of the sensor). These advantages include:

1) Use of actual probability of detection versus range and aspect rather than the "cookie cutter" W/2. The use of a "cookie cutter" detection pattern consistently overestimates the barrier probability of detection. In limited exercise of this model it was

seen that the maximum barrier effectiveness occurred when the patrol width was approximately one-third of the barrier.

2) Inclusion of decorrelation of environmental fluctuations through using the "relaxation time" model of detection.

3) Incorporation of aspect dependent source level data, if desired.

4) Ability to use any propagation loss function.

In addition, besides the computational efficiency discussed earler, the barrier model may be rerun using a smaller number of barrier and/or patrol segments without recomputing grid point probabilities. This is accomplished by changing the range of indices in the model over which the product of terms $\Pi_i q_i$ is computed.

AREA SEARCH ALGORITHM

The Measure of Effectiveness (MOE) currently used in the CSE&A program for area search is the probability of detecting a target randomly situated in area (A) given that the searcher has a particular sweep width (W) against the target and travels at velocity (V) searching during a time period (T). The equation for the probability of detection is:

$$P_D = 1 - \exp(-VWT/A)$$

The MOE to be developed in this section is the probability that there are no undetected targets in area A after a search of duration T. This is felt to be a more realistic MOE for area search than that used in the CSE&A program.

The targets for this algorithm are assumed to be located randomly in a two-dimensional field with the average number of targets per unit area equal to μ. That is, every small area, a, contains a target with probability μa. The probability of more than one target in a is negligible if a is sufficiently small. Also, the number of targets in non-overlapping regions are independent random variables. These assumptions are consistent with a Poisson distribution.

Let A be the area of a region within the field that is not necessarly small and let N_A be the number of targets in it. As developed in Washburn (Reference 1) the probability that area A contains n targets is

$$P(N_A=n) = \frac{(\mu a)^n}{n!} e^{-\mu A}, \quad n=0,1,2,\ldots,$$

This is the Poisson distribution and the field of targets is termed a "Poisson field."

The probability that exactly n targets are detected given that n targets are present is

$$P_n = \left(1-e^{-\frac{W\tilde{V}T}{A}}\right)^n$$

where

- P_n is the probability that exactly n targets are detected
- W is the sweepwidth
- $\tilde{V}$ is the effective search speed
- A is the area to be searched
- T is the time duration

The "effective speed" is the average relative speed between searcher and target assuming the angle between their velocity vectors are uniformly distributed between 0 and 2π.

$$\tilde{V} = \frac{1}{2\pi}\int_0^{2\pi}\sqrt{u^2+v^2-2uv\cos\theta}\, d\theta$$

By changing the variable of integration to $\psi = (\pi-\theta)/2$ and introducing $\sin\sigma = 2\sqrt{uv}/(u+v)$, the equation for $\tilde{V}$ reduces to:

$$\tilde{V} = \frac{2}{\pi}(u+v)E(\sin\sigma)$$

where $E(\sin\sigma)$ is the complete elliptic integral of the second kind and $\sin\sigma$ is as defined above.

The probability that there are no undetected targets in Area A after search of duration T becomes the summation of the individual terms $P_nP(N_A=n)$ and thus:

P(no undetected targets in A after search of duration T).

$$= \sum_{n=0}^{\infty} \frac{(\mu a)^n}{n!} e^{-\mu A}\left(1-e^{-\frac{W\tilde{V}T}{A}}\right)^n$$

letting $p = 1-e^{-\frac{W\tilde{V}T}{A}}$, multiplying each term by $e^{-p\mu A}e^{p\mu A}$ and regrouping we get:

$$P = \sum_{n=0}^{\infty} \frac{(p\mu A)^n}{n!} e^{-\mu A}\, e^{-\mu A(1-p)}$$

$$= e^{-\mu A(1-p)} \sum_{n=0}^{\infty} \frac{(p\mu A)^n}{n!} e^{-p\mu A}$$

where the infinite sum is over the individual terms of the Poisson distribution and is identically equal to 1. The expression therefore reduces to:

$$P = e^{-\mu A(1-p)}$$

$$= e^{-\mu A}e^{-\frac{W\tilde{V}T}{A}}$$

This algorithm had not been programmed at the time work was halted. In order to bring this development to completion, the sweep width must be computed and $\tilde{V}$ must be calculated. Models for computation of these two factors are available at Summit Research and the remainder of work on this algorithm would be to integrate all the components to allow for a more highly automated system eliminating the necessity for table look-ups and hand calculations.

SSN EFFECTIVENESS IN MULTIPLE ENGAGEMENT SCENARIO

No additional work past concept formulation occurred because of the termination of this task. Presented below is the concept formulation as proposed.

For multi-engagement models there are two obvious approaches that could be followed. One approach would be to simulate successive engagements in a Monte Carlo simulation. An alternative approach is to use Markov analysis. Monte Carlo simulations are time consuming and expensive both to create and to run. Markov processes, where adaptable, are simple to formulate and to obtain results.

The most significant requirement for formulating the multi-engagement situation as a Markov process is the identification of independent states. In a one-on-one engagement, independent states would reflect reduced systems capabilities on either side, or a change in information state. The following are examples of states for a submarine versus submarine engagement:

- all systems functioning and unalerted, for both submarines;

- all systems functioning and alerted, for both submarines;

- one submarine has reduced capability due to damage, other fully operational;

- both submarines have reduced capabilities due to systems damage;

- etc.

Terminal states, where the engagement ends, would have to be specified. These states would reflect the situations in which both parties no longer want to pursue the engagement any further. These would depend on the objectives of both sides. For some scenarios, damage to own ship or to the opponent will be sufficient for disengagement. In other situations, an engagement may continue until one submarine is disabled or destroyed, or the objective is accomplished.

Once the states are specified it is necessary to determine the probability of ending in that state as an outcome of an engagement. Each set of transition probabilities must be calculated assuming the engagement starts with the combatants in each of the initial states. Therefore, the engagement analysis must be performed for each of the states.

While a good deal of analysis must be performed for this approach, in general, it is easier and faster than using Monte Carlo simulations. The key to a successful use of Markov techniques is the identification of states. Each state must reflect a significant change of capabilities. If too many states are specified, the analysis and computation can become overwhelming. If too few are selected, the sensitivity of results can be lost.

This same approach can be used for multiple unit scenarios. This approach was successfully used in the FORCE MIX study. The states for a multiple unit engagement reflect decreases in the number of units available.

The more complex the problem, the greater the advantage of Markov analysis over Monte Carlo simulations.

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1. Search and Detection, Alan R. Washburn, Military Applications Section, ORSA, May 1981

APPENDIX A

Presented in this appendix is the indexing scheme for reconstructing the 2Np(N+1) possible tracks used in the barrier model. Figure A-1 contains the FORTRAN code pertinent to this reconstruction. This code assumes the existence of a three dimensional array, DQS(L,KM,II). An element of this array is the probability of not detecting for the segment of relative track ending at grid point (L,KM). The II index determines whether this segment enters the grid point from the right or left. That is, if II=1 then the segment is from (L+1,KM+1) to (L,KM) and if II=2 it is from (L+1,KM-1) to (L,KM).

From Figure A-1, lines 1-3 set the indices for the loops (lines 4,5) for all relative starting positions of barrier and transitor submarines. There are (NSEG+1) starting positions for the transitor submarine (line 4) across the barrier width and (NPSEG+1) starting position for the barrier submarine (line 5). Indices in lines 2 and 3 center the patrol segments over the barrier width.

Code in lines 6-8 determines the index value for line 10. This index (JU) is associated with the possible directions of travel of the barrier submarine at its initial starting position. The index JU will equal 2

```
      IB = NSEG+1
      M1 = (NSEG-NPSEG)/2.0 +1
      M2 = M1 + NPSEG
      DO 500 K = 1, IB
      DO 500 M = M1, M2
      JU = 2
      IF(M.EQ.M1) JU = 1
      IF(M.EQ.M2) JU = 1
      I = 1
      DO 600 J = 1, JU
      IC = IC + 1
      TQ = 1.0
      MJ = M
      DO 700 L = 1, LB
      II = 1
      IF(MJ.EQ.M2) I = -1
      IF(MJ.EQ.M1) I = 1
      KM = MJ -K + IB
      IF(I.EQ.-1) II = 2
      DQSS = DQS(L,KM,II)
      TQ = TQ*DQSS
      MJ = MJ + I
  700 CONT.
      TBEFF = 1.0 - TQ
      BEFF = BEFF + TBEFF
      I = -1
  600 CONT
  500 CONT
      BEFF = BEFF/IC
```

Figure A-1 CODE FOR RECONSTRUCTING RELATIVE TRACKS

unless the barrier submarine starts at one of the endpoints of its patrol width (M1 or M2) and then only one direction is possible.

The index I determines the relative direction of the barrier submarine for each segment of track. It is +1 when the barrier submarine is moving to the right and -1 when moving to the left. The value of I determines the index II in the DQS array mentioned previously. The first time through the J loop (lines 10-27) the value is set to 1, (line 9) the second time through the value is set to -1 (line 26) for the different initial directions of travel of the barrier submarine. If the initial barrier submarine position is at the extreme right of its patrol then only an initial position applies (I = -1) and line 16 correctly sets I = 1 (line 9) to a -1 for this track.

The total number of tracks are accumulated by the expression in line 11 which was initialized to zero before starting this reconstruction. Line 12 initializes the value of the probability of not detecting along any relative track. Line 13 establishes a dummy variable that can modified without changing the value of the M index from line 5.

The probability of not detecting along one of the relative tracks is computed by lines 14-23. As the transitor moves from its initial to its final position it traveres LB range increments. Depending on the initial position of the transitor across the barrier width and the initial position and direction of the barrier submarine, (initial values of K, M, and I). The track is reconstructed by varying the KM index (line 18) by ±1 for each range increment in L depending on whether the barrier submarine would be moving to the left or right during this increment. Lines 16 and 17 determine whether the endpoints of the patrol are reached and a change of direction is necessary. Line 21 is the probability of not detecting along the track (P(not detecting) = $\prod_{LB} q_L$).

Line 24 is the probability of detecting along the track and line 25 accumulates this probability, which is eventually divided by the total number of tracks IC (line 29) yielding the mean probability of detection for the moving barrier.